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Effect of spatial and temporal scale on simulated groundwater recharge investigations

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ABSTRACT

Hydrologic model input datasets such as climate, land use, elevation, soil, and geology information are available in a range of scales for use in water resources investigations. Smaller spatial and temporal scale input data allow groundwater recharge models to simulate more physically realistic processes and presumably result in more accurate estimates of groundwater recharge. Projected climate data are, therefore, often downscaled to smaller spatial and temporal scales for use in these models. It is unknown, however, if increasingly smaller-scale climate data produce substantially different simulated recharge results, either in magnitude or trend. Also, even if simulated recharge results are different at a higher space and time resolution, simulation at coarser resolution might be adequate to provide recharge information at decision scales (e.g., meeting Colorado River compact requirements on a ten-year moving average basis). Historical climate datasets at three spatial (~800 m, ~4 km, and ~12 km) and two temporal (daily and monthly) scales were used in a Soil Water Balance (SWB) model of the upper Colorado River basin (UCRB) to simulate groundwater recharge over the water-year 1982–2014 time period. The magnitude of annual and moving ten-year annual average recharge results for daily climate data were within 5% and 7% of ~4 km results for ~800 m and ~12 km climate data, respectively, with deviations from 1982 to 2014 means within 1% and 3% (median), respectively. Comparison of simulated recharge results using the coarsest spatial and temporal climate data with results from the finest scale data indicated similar small differences over ten-year moving annual averages, over water years, and during high recharge months. While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, were substantial during some seasonal comparisons, trends in recharge were almost identical across scales, leading to similar conclusions about change from "normal". Considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale input data may be sufficient for water resources managers who need to understand changes in trends in groundwater recharge over water-year or longer time periods.

1. Introduction

For water resources managers seeking information on projected groundwater resources, investigation of impacts from projected climate change on groundwater systems often involve the use of hydrologic model simulations with climate data from general circulation models (GCMs) (e.g., Allen et al., 2010; Crosbie et al., 2011; Kopytkovskiy et al., 2015). Climate output from GCMs is typically provided at relatively coarse spatial resolutions of about 100–200 km on each cell side, which are then downscaled to finer resolutions (e.g., ~12 km (1/8th degree) monthly datasets (Brekke et al., 2013) and ~6 km (1/16th degree) daily datasets (Pierce et al., 2014)). In groundwater recharge simulations, finer spatial-scale models permit incorporation of more realistic variations in geologic, land use, and topographic information. Likewise, recharge in many areas of the southwestern United States occurs on a daily (or sub-daily) time scale (Stonestrom et al., 2007). Considerable time and effort is therefore expended in downscaling GCM output to smaller spatial and temporal scales for use in hydrologic models. Published studies of simulated groundwater recharge utilize spatial data ranging from relatively small scales (i.e., 20 m to 100 m) often used with quasi-two-dimensional models (Scibek and Allen, 2006; Nyenje and Batelaan, 2009; Towes and Allen, 2009), to fractional-degree (i.e., ~5 km to ~25 km) scales (Barnett et al., 2007; Christensen et al., 2004; Crosbie et al., 2010, 2013; Mileham et al., 2009; Niraula et al., 2017). Daily time steps are commonly used in published recharge simulation investigations (Ali et al., 2012; Barnett et al., 2007; Crosbie et al., 2010, 2011; Dams et al., 2012; Holman et al., 2009; McCallum et al., 2010; Mileham et al., 2009; Scibek and Allen, 2006; Toews and Allen, 2009; Niraula et al., 2017). Recently, Tillman et al., (2016, 2017a, b) used downscaled projected and historical climate data at 1/8th degree spatial and daily temporal scales to simulate groundwater recharge in the upper Colorado River basin (UCRB). The value of higher resolution model-

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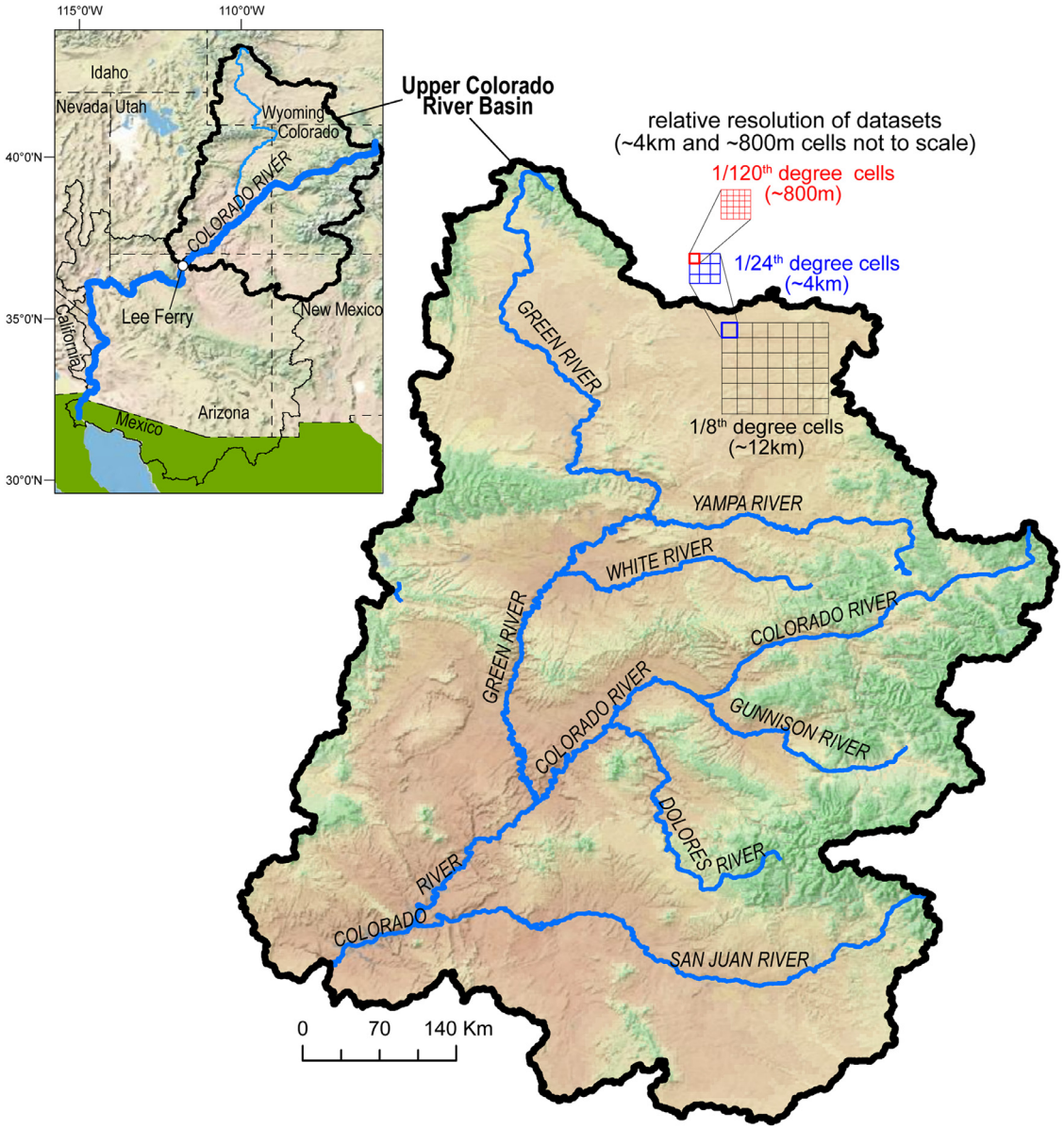

Fig. 1. Location of the upper Colorado River basin study area within the southwestern United States.

ing, particularly when providing water managers with recharge information at decision scales such as meeting compact requirements on a ten-year moving average basis in the Colorado River basin (Colorado River Compact, 1922), is unclear. While smaller scales allow more realistic hydrologic processes to be simulated, it is unknown whether meaningfully different groundwater recharge simulations, either in magnitude or trend, result from using smaller versus larger scale climate data. This paper presents results from a new investigation of simulated groundwater recharge in the UCRB using historical climate data at the ~12 km (1/8th degree), ~4 km (1/24th degree), and ~800 m (1/120th degree) scales on both daily and monthly time steps. These scale choices correspond to available contemporary climate data from archives such as the Downscaled Climate and Hydrology Projections (Maurer et al., 2007) and PRISM (PRISM Climate Group, 2016) that are routinely used in a range of water resources planning studies (e.g., Tillman et al., 2017a,b; Bureau of Reclamation, 2017 for others). Simulated basin-scale groundwater recharge results for the different spatial and temporal scale data are compared on seasonal, annual, and moving ten-year average basis. Results of the magnitude of simulated groundwater recharge are compared as well as deviations from the period-of-record mean, which may be of more interest to water managers to whom changes from 'normal' are important.

1.1. Study area

This study investigates the effect of spatial and temporal scale on groundwater recharge simulations in the upper Colorado River basin (Fig. 1). The Colorado River is an important source of water in the southwestern United States (U.S.), supplying the industrial and domestic water needs of more than 38 million people in the U.S. and Mexico (Colorado River Basin Salinity Control Forum, 2013; Bureau of Reclamation, 2011). At Lake Mead in Arizona, downstream of which nearly all of the Colorado River water is used, the UCRB contributes almost 90% of the flow in the River (U.S. Geological Survey, 2016). The UCRB stream system receives an estimated 30–50% of its flow from groundwater discharge (Rumsey et al., 2015; Miller et al., 2014). In his investigation of the hydrologic and groundwater-flow systems in the UCRB, Geldon (2003) estimates about 8.1 km^3 of annual recharge to all groundwater systems in the area, excluding the upper San Juan basin which was not part of the study. For the current study, the UCRB is defined as the Colorado River drainage area that is upstream of the compact point

at Lee Ferry, Arizona plus the Great Divide closed basin, as delineated by the U.S. Geological Survey region 14 hydrologic unit code (Fig. 1; U.S. Geological Survey, 2018).

2. Methods and data

Groundwater recharge in the UCRB was simulated with the distributed-parameter soil-water balance (SWB) model for this spatial and temporal scale study (Westenbroek et al., 2010). Groundwater recharge is estimated by the SWB model at daily time steps by calculating water-balance parameters using a modified Thornthwaite-Mather soil-water-balance accounting method, with groundwater recharge estimated within each model cell of the study area (Thornthwaite, 1948; Thornthwaite and Mather, 1957). The SWB model calculates water sources and sinks within each cell of the model domain from landscape characteristics and climate data. Groundwater recharge is then estimated as the difference between the change in soil moisture and these water sources and sinks. SWB model simulations require spatially gridded datasets including daily minimum temperature, daily maximum temperature, daily precipitation, hydrologic soil group, land cover, available soil-water capacity, and overland flow direction. SWB simulations also require input datasets in a tabular format including vegetation rooting depths, runoff curve numbers, interception values, and maximum daily recharge values for each combination of land-cover type and hydrologic soil group. A detailed discussion of input datasets, computational details, and limitations of the SWB model are presented in the supplementary material. For each combination of spatial and temporal scale climate data, the UCRB SWB model was initially run for a period of 10 years using initial conditions of 100% soil moisture and 0% snow cover. The final soil moisture and snow cover conditions at the end of the 10 year initialization period were then used as initial conditions for full 1981–2014 model runs.

Daily climate data for the 1981–2014 time period at a 1/24th degree (~4 km) spatial scale (Fig. 2, middle panel) covering the UCRB study area were obtained from the PRISM Climate Group at Oregon State University (PRISM Climate Group, 2016). The daily ~4 km PRISM climate data were aggregated to 1/8th degree (~12 km) spatial scale (Fig. 2, bottom panel) and disaggregated to 1/120th (~800 m) spatial scale (Fig. 2, top panel) climate data. Disaggregation from coarse to finer scale data (~4 km to ~800 m) was performed using the bilinear interpolation method, specifically the '*linint2*' function from the National Center for Atmospheric Research (NCAR) Command Language (NCL; NCAR, 2017). This method has been used by Reclamation and Reclamation collaborators to downscale relatively coarse (~100–200 km) climate projections to finer spatial scales (1/8th degree) using the Bias Correction and Spatial Disaggregation (BCSD) statistical downscaling algorithm. Bilinear interpolation is a two-dimensional version of linear interpolation that is performed on a rectangular grid of points. A weighted average of the four surrounding grid points is used to calculate the interpolated value (National Institute of Standards and Technology, 2018). Fine grid to a coarse grid (~4 km to ~12 km) aggregation was performed using the '*area_hi2lores*' NCL function (NCAR, 2017). This function uses local area averaging to interpolate from a high resolution rectilinear grid to a low resolution rectilinear grid. A low resolution rectangular grid is created from high resolution grid points by averaging them based on their fractional contribution to the low resolution grid point. Though NCL provides a number of re-gridding functions, the '*linint2*' and '*area_hi2lores*' for disaggregation and aggregation, respectively, were used in this study because they have been used previously in developing and studying contemporary climate datasets from GCM projections (e.g., Maurer et al., 2007; Gutmann et al., 2014).

Daily precipitation and temperature data at the three spatial scales also were aggregated into monthly stress periods for SWB simulations. Daily precipitation data were summed over each month and then the daily average for a month assigned to each day in that month. Daily minimum and maximum temperatures were each averaged over each month with the daily average for a month then assigned to each day in that month. In this way, the SWB model, which runs on a daily time step, could be used to simulate groundwater recharge as if only monthly climate data were available.

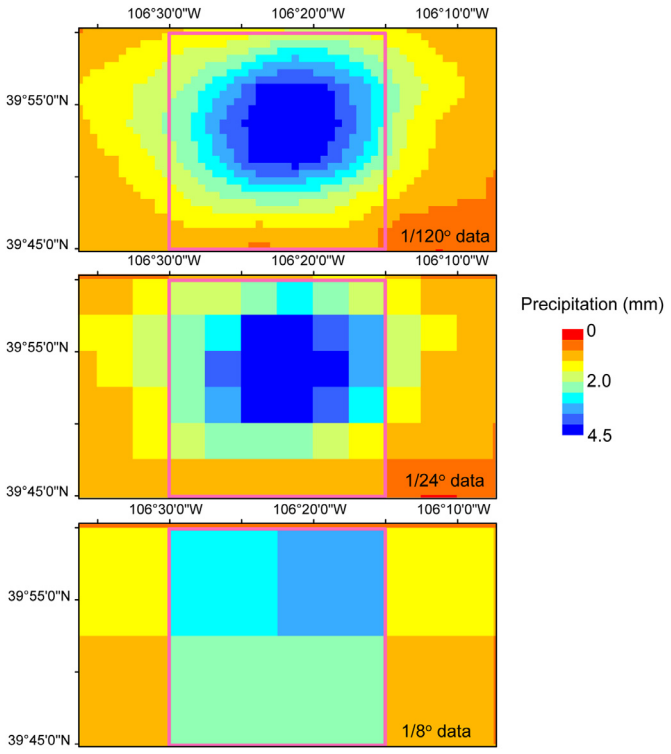

Fig. 2. Example PRISM precipitation data for June 1, 1981 at 1/120th degree (upper panel), 1/24th degree (middle panel), and 1/8th degree spatial scales. Average precipitation within the pink square, comprising four 1/8th degree cells, is 2.5 mm for all three spatial scales.

To summarize and compare temperature data across spatial and temporal scales, potential evapotranspiration (PET) values are used instead of temperature values directly. PET values are a convenient measure of the effect of basin-wide temperature change and have more hydrologic meaning than temperature alone. PET estimates in this study are directly related to maximum and minimum daily temperatures and are computed as a volume of water, which is used directly in the water-balance equation (see supplementary material for complete description).

Using the "numpy" package in Python scripts, precipitation input data and SWB output of PET, recharge, and snowmelt in dimensions of length (i.e., inches) were converted to dimensions of volume (i.e., m^3) and summed over the UCRB study area on daily time steps. The distributed precipitation and SWB output values were multiplied by their associated individual cell areas within the study area. Cell areas within the UCRB range from 15.5 km^2 along the northern boundary to 17.6 km^2 along the southern boundary, for the 1/24th degree (~4 km) spatial scale data. Precipitation and simulation results in m^3 were then summarized, analyzed, and compared in Excel using Visual Basic for Applications (VBA) scripts. Recharge simulations using three spatial and two temporal scales were run, with results compared over ten-year moving average, water-year, and seasonal time periods.

3. Results and discussion

UCRB groundwater recharge was simulated with the SWB model at three spatial and two temporal scales. Results from simulations using ~12 km and ~800 m daily climate data are compared with simulation results using the original ~4 km daily PRISM climate data. Similarly, simulation results using ~12 km and ~800 m climate data on

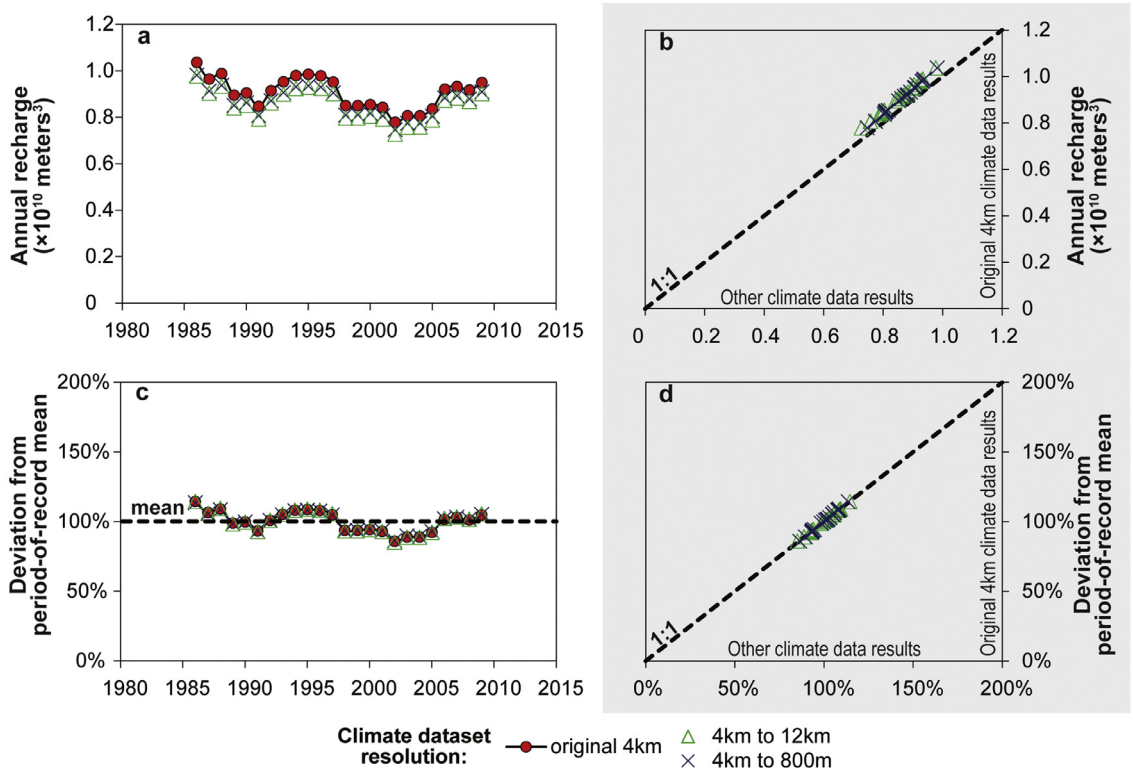

Fig. 3. Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800 m, ~4 km, and ~12 km daily climate data. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data. Symbols on time series charts are placed in the middle of the ten-year averaging period.

monthly time steps are compared with simulation results using ~4 km monthly climate data. For both daily and monthly climate data, results are summarized and compared over ten-year average annual periods, over water years, and over three-month seasons. All UCRB groundwater recharge modeling results are available at the U.S. Geological Survey ScienceBase web site (Tillman, 2017). Average annual recharge simulated during the 1981–2014 time period by the SWB model using ~4 km climate data over the same UCRB area as the Geldon (2003) study was 7.9 km^3, representing 2.5% difference with the Geldon (2003) estimate.

3.1. Results from simulations with daily climate data

3.1.1. Ten-year moving average comparisons

Annual simulated groundwater recharge averaged over ten-year periods, moving every year, for the original ~4 km daily PRISM climate data ranged from a high of 10.4 billion (B) m^3 over the 1982–1991 time period to a low of 7.8B m^3 over the 1998–2007 time period (Fig. 3a). Recharge results using ~12 km and ~800 m climate data follow the same temporal pattern as the ~4 km results (Fig. 3a), but are systematically less than the ~4 km results (Fig. 3b). The amount of reduced recharge, however, is relatively small, with a median percentage change from the ~4 km results (difference divided by the ~4 km result) of 4.6% for the ~800 m results and 5.8% for the ~12 km results (Fig. 3b, Table 1). The temporal trend in simulated recharge, defined here as deviation from the 1982–2014 period-of-record (POR) average for each spatial scale, ranged from 114% to 86% of the POR mean for the ~4 km results (Fig. 3c). Recharge trends for the ~12 km and ~800 m results are even more similar to the ~4 km trends than the recharge magnitude results, with median percentage change from the ~4 km ten-year average annual recharge trends of less than 1% for both the ~800 m and ~12 km results (Fig. 3d, Table 1). Over ten-year moving annual averages, recharge simulations using daily climate data at the smallest spatial scale investigated do not differ substantially from simulations at the larger scales, either in absolute magnitude or in trend.

3.1.2. Water-year comparisons

UCRB simulated recharge over water years from 1982 through 2014 using the original ~4 km daily PRISM climate data ranged from a high of 16.6B m^3 during water year 1993 to a low of 2.9B m^3 during water year 2002 (Fig. 4a). Similar to the ten-year moving annual average results, water-year recharge results using ~12 km and ~800 m climate data follow the same temporal pattern as the ~4 km results (Fig. 4a), also are systematically less than the ~4 km results (Fig. 4b), and only by a similarly small amount (median percentage change from the ~4 km results of 4.7% for the ~800 m results and 6.3% for the ~12 km results; Fig. 4b; Table 1). Simulated recharge in a few low-recharge years, however, is substantially less for the ~12 km climate data than for the ~4 km climate data, including a 13.6% decrease in 1992, a 13.1% decrease in 2012, and a 12.1% decrease in 2002 (Fig. 4a). Differences in simulated recharge in these years are in contrast to the very small differences in precipitation of <0.18% and potential evapotranspiration (PET) of <0.03% (Figs. S2 and S3 in the supplementary material). Deviation from the POR average is predictably greater for the water-year results compared with the smoothed ten-year moving annual average results (Fig. 4c). Water-year recharge results using the ~4 km climate data are as much as 76% greater and 70% less than the 1982–2014 average (Fig. 4c). Recharge trends for the ~12 km and ~800 m results also are similar to the ~4 km trends, with median percentage change from the ~4 km water-year recharge trends of less than 3% for both the ~800 m and ~12 km results (Fig. 4d, Table 1). Unlike the ten-year moving annual average results, water-year deviations from POR means are

Table 1
Summary of percentage change comparison of simulated groundwater recharge in the upper Colorado River basin between simulations using daily ~4 km climate data and simulations using ~800 m and ~12 km daily climate data over ten-year moving annual average, water-year, and seasonal time periods.

		|Percentage change from ~4 km recharge results[a]|			
		Magnitude of recharge		Deviation from period-of-record mean	
Time period of comparison	Spatial resolution	Median	25th–75th percentile	Median	25th–75th percentile
Ten-year moving average	~800 m	4.6	4.2–4.9	0.3	0.2–0.5
	~12 km	5.8	5.5–6.1	0.3	0.2–0.5
Water year	~800 m	4.7	3.8–5.5	0.9	0.4–1.3
	~12 km	6.3	4.6–9.1	2.7	0.9–3.7
December–February (8% of annual recharge)	~800 m	4.1	1.1–7.1	3.4	1.3–7.4
	~12 km	6.9	3.7–9.4	6.6	3.4–9.0
March–May (71% of annual recharge)	~800 m	4.0	2.4–5.0	1.4	0.8–2.1
	~12 km	4.4	2.2–7.1	4.5	1.8–6.6
June–August (16% of annual recharge)	~800 m	20.5	17.9–25.8	4.7	2.4–9.8
	~12 km	35.8	27.7–43.1	12.3	5.8–21.1
September–November (5% of annual recharge)	~800 m	18.5	10.3–22.9	6.7	3.8–9.7
	~12 km	15.7	9.8–25.2	9.2	4.1–17.9

[a] Absolute value of difference from ~4 km results divided by ~4 km results, in percent.

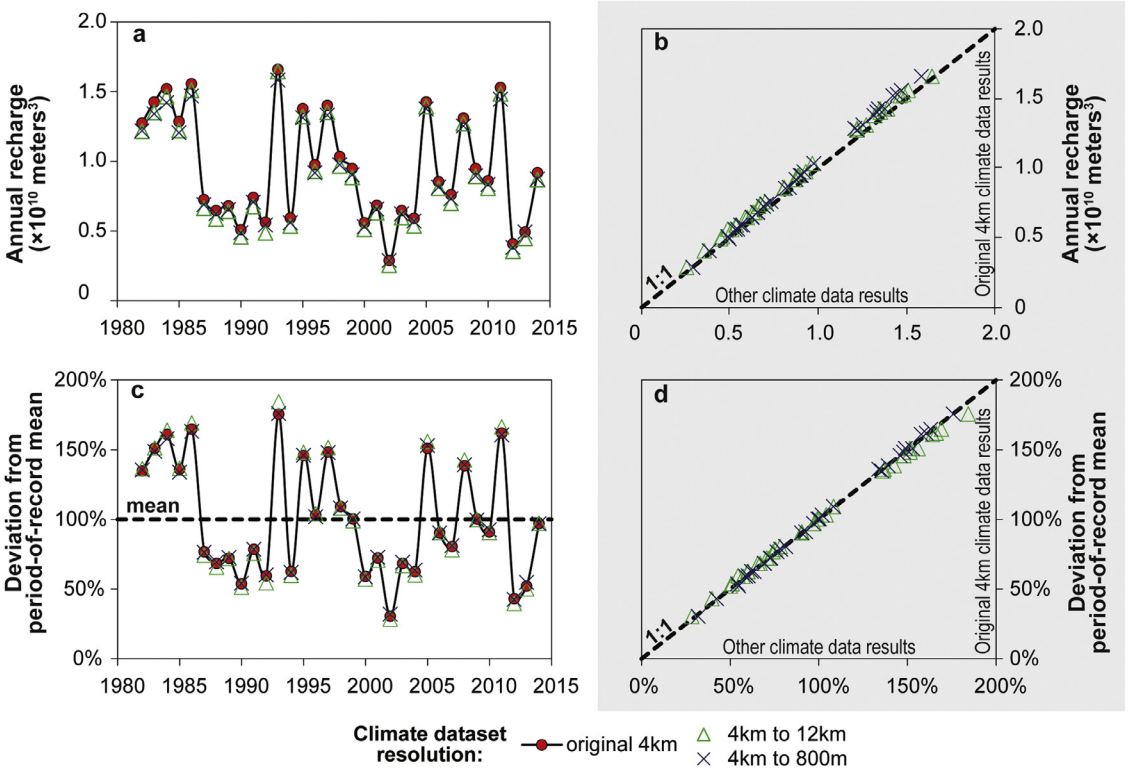

Fig. 4. Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800 m, ~4 km, and ~12 km daily climate data. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

less for ~4 km results than for the other spatial resolutions in several years, particularly the ~12 km results (Fig. 4d). With the exception of a few years, water-year simulation results for the 1982–2014 time period for all spatial resolutions are similar in both magnitude and trend of recharge.

3.1.3. Seasonal comparisons

Simulated recharge results from daily climate data also were summarized in water-years 1982 to 2014 over seasonal time periods including the winter months of December–February (DJF), spring months of March–May (MAM), summer months of June–August (JJA), and fall months of September–November (SON). Winter and spring seasonal recharge, which account for 8% and 71% of simulated annual recharge in the UCRB, respectively, showed similar small differences in both magnitude and trend between simulations using the different spatial resolution datasets as were seen with the water-year and ten-year moving annual average results (Figs. S4 and S5 in the supplementary material). Median differences in DJF recharge magnitude from ~4 km results were 4.1% and 6.9% for ~800 m and ~12 km climate data, respectively, and median MAM differences in recharge magnitude from ~4 km results were 4% for both ~800 m and ~12 km climate data (Figs. S4 and S5 in the supplementary material; Table 1). Simulated recharge in the JJA summer months, which account for 16% of simulated annual UCRB recharge, resulted in substantial differences in recharge magnitude be-

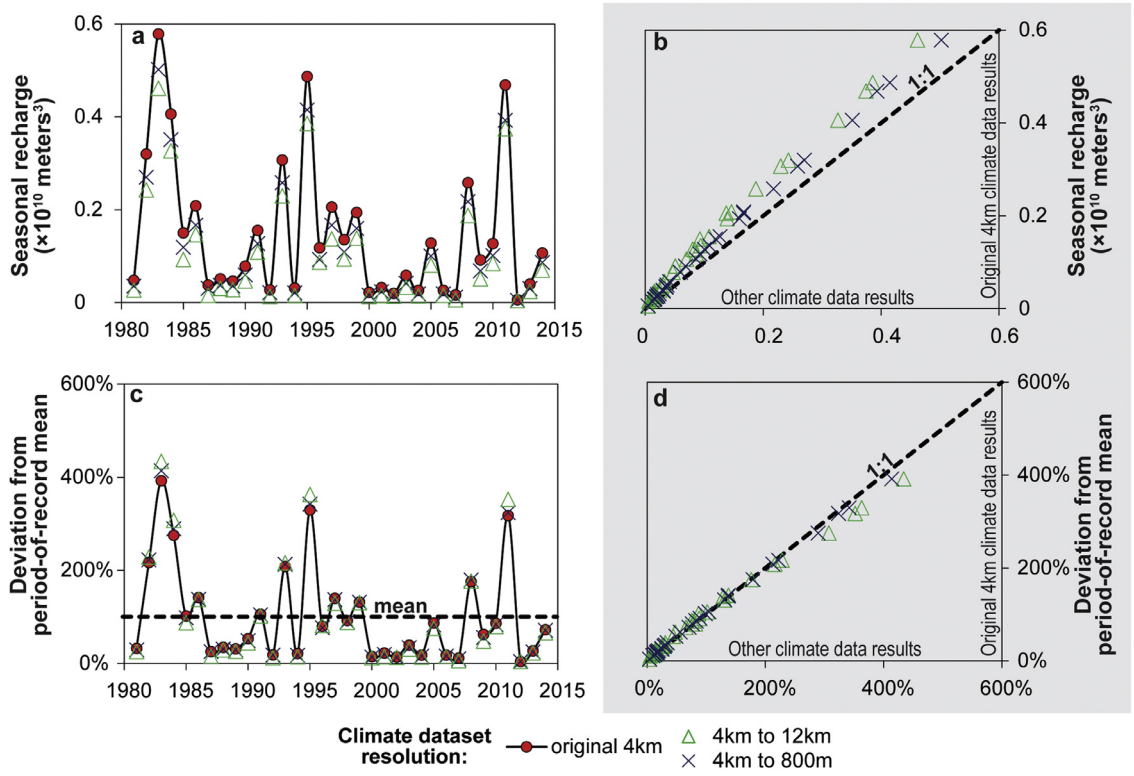

Fig. 5. Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800 m, ~4 km, and ~12 km daily climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

tween the ~4 km climate data and the ~800 m (median difference of 20.5%) and ~12 km (median difference of 35.8%) climate data (Fig. 5a, b; Table 1). The somewhat higher simulated JJA recharge using ~4 km climate data than simulations using ~800 m or ~12 km data cannot be explained by differences in either precipitation (Fig. S6 in the supplementary material) or PET (Fig. S7 in the supplementary material), both of which differ by less than 0.2% from ~4 km data for both resolutions. Simulated snowmelt in JJA, however, differs from ~4 km results by a similar amount to differences in recharge results, with a 15% median difference in snowmelt for the ~800 m climate data and a 35% median difference for the ~12 km data (Fig. 6). Differences in temperature between the different spatial datasets, particularly when temperatures are near freezing, in relatively limited high-altitude areas of the UCRB can result in differences in the amount of snowcover and subsequent differences in the amount of snowmelt during warmer months. These potentially small temperature differences in limited areas would not show up in the UCRB-wide summary of temperature in the PET comparisons (Fig. S7 in the supplementary material). Trends in JJA recharge from simulations using the different spatial resolutions, however, were more similar than magnitude results, with a median difference of 4.7% for the ~800 m results and a median difference of 12.3% for the ~12 km results, compared with results from the ~4 km climate data (Fig. 5c,d; Table 1). Recharge magnitude during fall months of September–November differs between simulations using the different spatial resolutions somewhat less than during JJA, with median percentage change of 18.5% and 15.7% for ~800 m results and ~12 km results compared with results from the ~4 km climate data (Fig. S8 in the supplementary material; Table 1). Differences in trends in SON recharge are similar to those from JJA, with median differences of 6.7% and 9.2% for ~800 m results and ~12 km results compared with results from the ~4 km climate data (Fig. S8 in the supplementary material; Table 1). Simulated recharge in SON, however, is only about 5% of the total annual amount for the UCRB.

3.2. Results from simulations with monthly climate data

3.2.1. Ten-year moving average comparisons

Daily precipitation and temperature data at the three spatial scales were aggregated into monthly stress periods for SWB simulations as described previously. Annual simulated groundwater recharge averaged over ten-year periods, moving every year, using the ~4 km monthly climate data ranged from a high of 9.5 billion (B) m^3 over the 1982–1991 time period to a low of 6.8B m^3 over the 1998–2007 time period (Fig. 7a). Recharge results using ~4 km monthly climate data were 6.3–12.5% less than results using ~4 km daily data over comparable time periods (Fig. 7a). As with the daily climate data results, recharge results using ~12 km and ~800 m monthly climate data follow the same temporal pattern as the monthly ~4 km results (Fig. 7a), but are systematically less than the ~4 km results (Fig. 7b). The amount of reduced recharge from monthly data is similar to comparative reductions from daily climate results, with a median percentage change from the ~4 km results of 3.6% for the ~800 m results and 5.9% for the ~12 km results (Fig. 7b; Table 2). The temporal trend in simulated recharge ranged from 116% to 83% of the POR mean for the monthly ~4 km results, with nearly identical deviations from POR mean as results from daily ~4 km climate data (Fig. 7c). Recharge trends for the monthly ~12 km and ~800 m results also are nearly identical to the ~4 km trends (Fig. 7d; Table 2).

3.2.2. Water-year comparisons

UCRB water-year simulated recharge over the 1982–2014 time period using monthly ~4 km climate data ranged from a high of 15.7B m^3 during water year 1993 to a low of 2.6B m^3 during water year 2002 (Fig. 8a). Recharge results using ~4 km monthly climate data were from

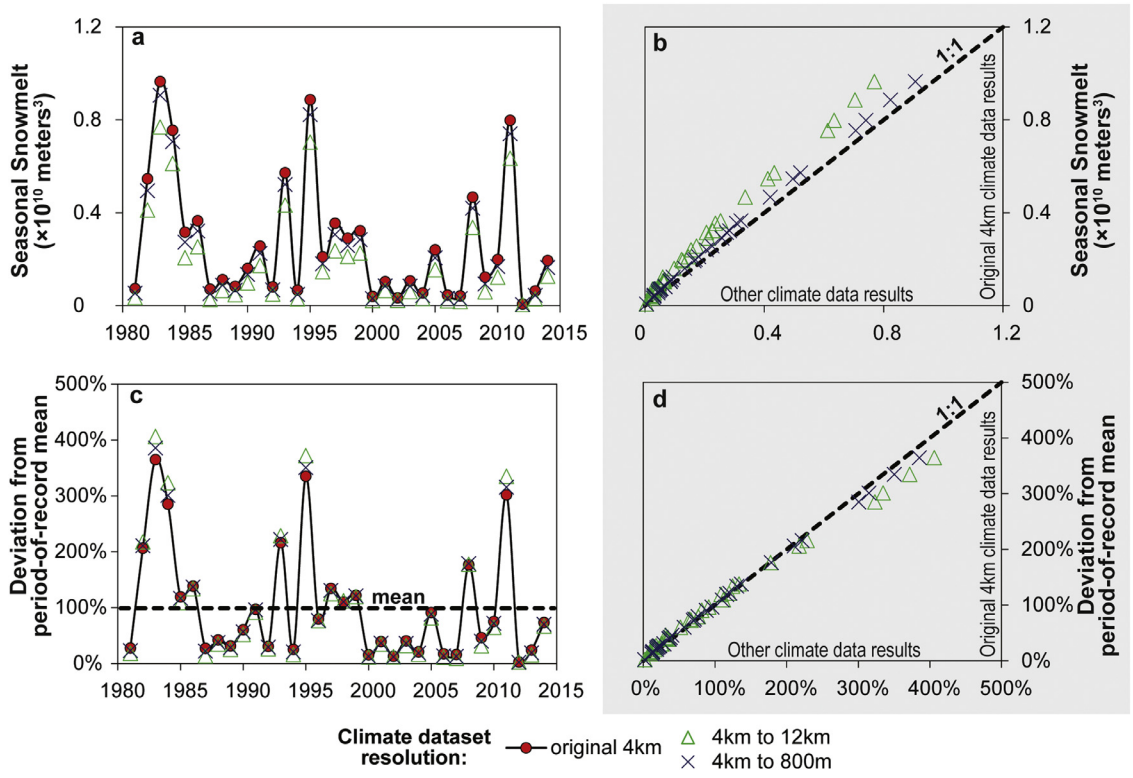

Fig. 6. Simulated snowmelt in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800 m, ~4 km, and ~12 km daily climate data. Results presented as (a) magnitude of seasonal snowmelt through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of seasonal snowmelt from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

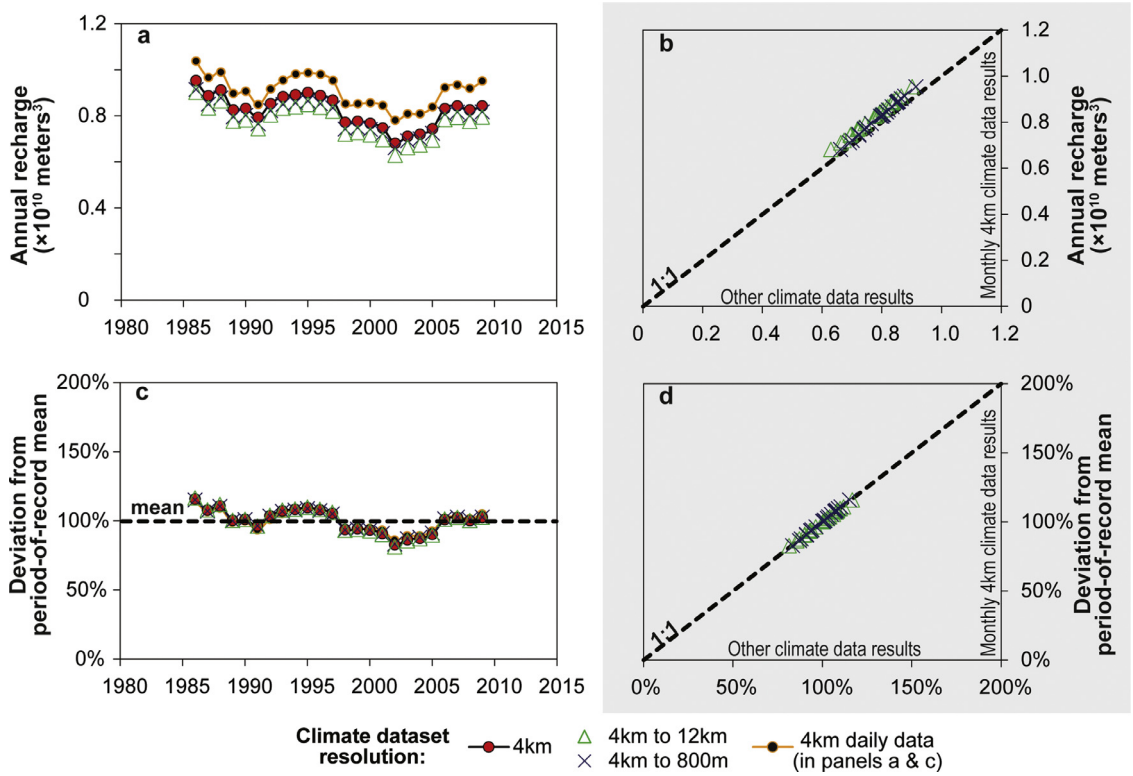

Fig. 7. Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800 m, ~4 km, and ~12 km monthly climate data. Simulation results from daily ~4 km climate data provided for reference. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data. Symbols on time series charts are placed in the middle of the ten-year averaging period.

Table 2
Summary of percentage change comparison of simulated groundwater recharge in the upper Colorado River basin between simulations using monthly ~4 km climate data and simulations using ~800 m and ~12 km monthly climate data over ten-year moving annual average, water-year, and seasonal time periods.

		|Percentage change from ~4 km recharge results[a]|			
		Magnitude of recharge		Deviation from period-of-record mean	
Time period of comparison	Spatial resolution	Median	25th-75th percentile	Median	25th-75th percentile
Ten-year moving average	~800 m	3.6	3.1–3.8	0.4	0.2–0.5
	~12 km	5.9	5.7–6.5	0.3	0.1–0.6
Water year	~800 m	3.5	2.8–4.2	0.9	0.4–1.5
	~12 km	6.9	4.4–8.5	2.5	1.5–4.0
Decembe–February (3% of annual recharge)	~800 m	16.2	10.7–28.9	10.4	5.2–22.5
	~12 km	14.6	7.8–31.3	14.5	7.7–31.3
March–May (68% of annual recharge)	~800 m	1.4	0.8–2.8	1.5	0.7–2.9
	~12 km	4.7	2.1–7.1	4.4	2.5–6.8
June–August (27% of annual recharge)	~800 m	19.1	14.9–23.2	6.3	2.3–9.2
	~12 km	32.1	24.7–40.9	11.9	5.2–21.0
September–November (2% of annual recharge)	~800 m	25.4	13.2–30.9	8.4	4.8–18.8
	~12 km	29.8	16.7–40.1	18.9	10.5–34.5

[a] Absolute value of difference from ~4 km results divided by ~4 km results, in percent.

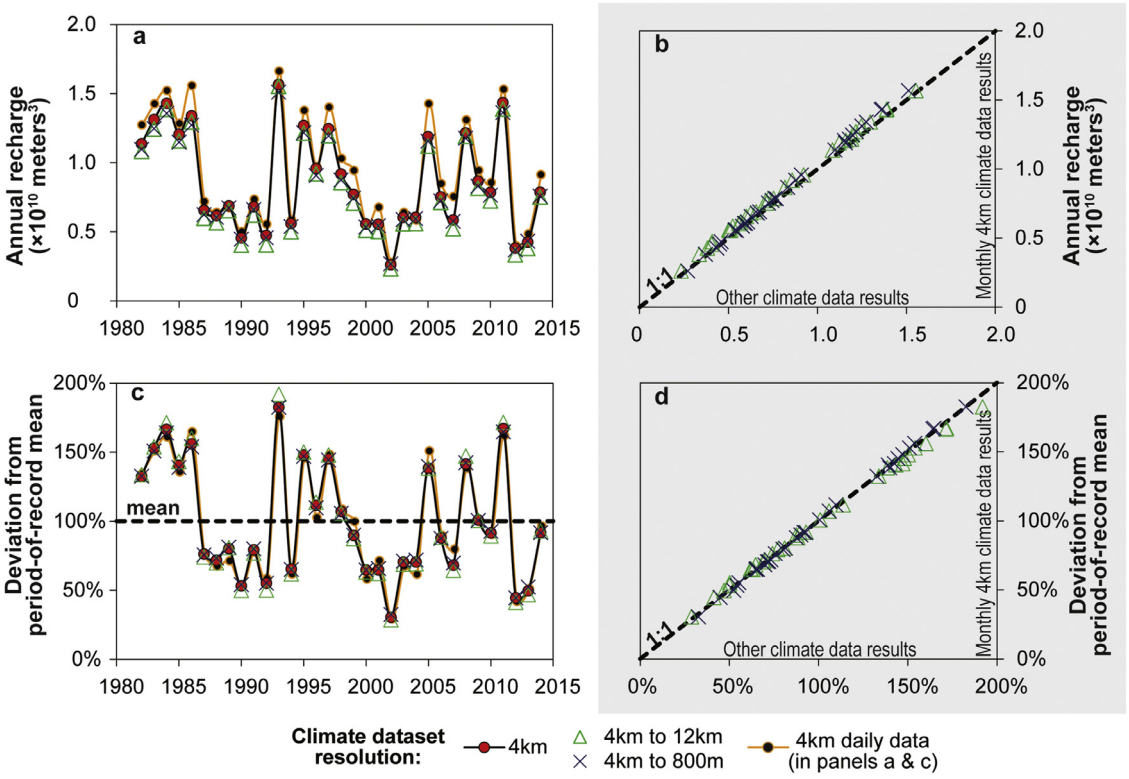

Fig. 8. Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800 m, ~4 km, and ~12 km monthly climate data. Simulation results from daily ~4 km climate data provided for reference. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

2.8% more in 2004 to 22.8% less in 2007 than results using ~4 km daily data over comparable time periods, with most water-year values about 10% less (Fig. 8a). Similar to water-year results using daily climate data, water-year recharge results using ~12 km and ~800 m monthly climate data follow the same temporal pattern as the ~4 km monthly data results (Fig. 8a), and also are systematically less than the ~4 km monthly results by a small amount (Fig. 8b). The median percentage change of ~800 m and ~12 km monthly data results from ~4 km monthly data results is 3.5% and 6.9%, respectively (Fig. 8b; Table 2). Simulated recharge in a few low-recharge years also is substantially less for the ~12 km monthly climate data than for the ~4 km monthly climate data, including a 14.3% decrease in 1992 and a 12.7% decrease in 2012. In a similar manner to daily climate data results, differences in monthly climate data simulated recharge in these years are in contrast to the very small differences in precipitation of <0.17% and potential evapotranspiration (PET) of <0.03% (Fig. S9 and S10 in the supplementary material). Deviation of water-year results from the 1982–2014 average are similar between results from all spatial resolution data on a monthly time step and between the monthly and daily ~4 km climate data results (Fig. 8c, d). Median percentage change from the monthly ~4 km recharge trends is less than 2.5% for both the monthly ~800 m and ~12 km results (Fig. 8d; Table 2). Median percentage change of monthly ~4 km climate data results from

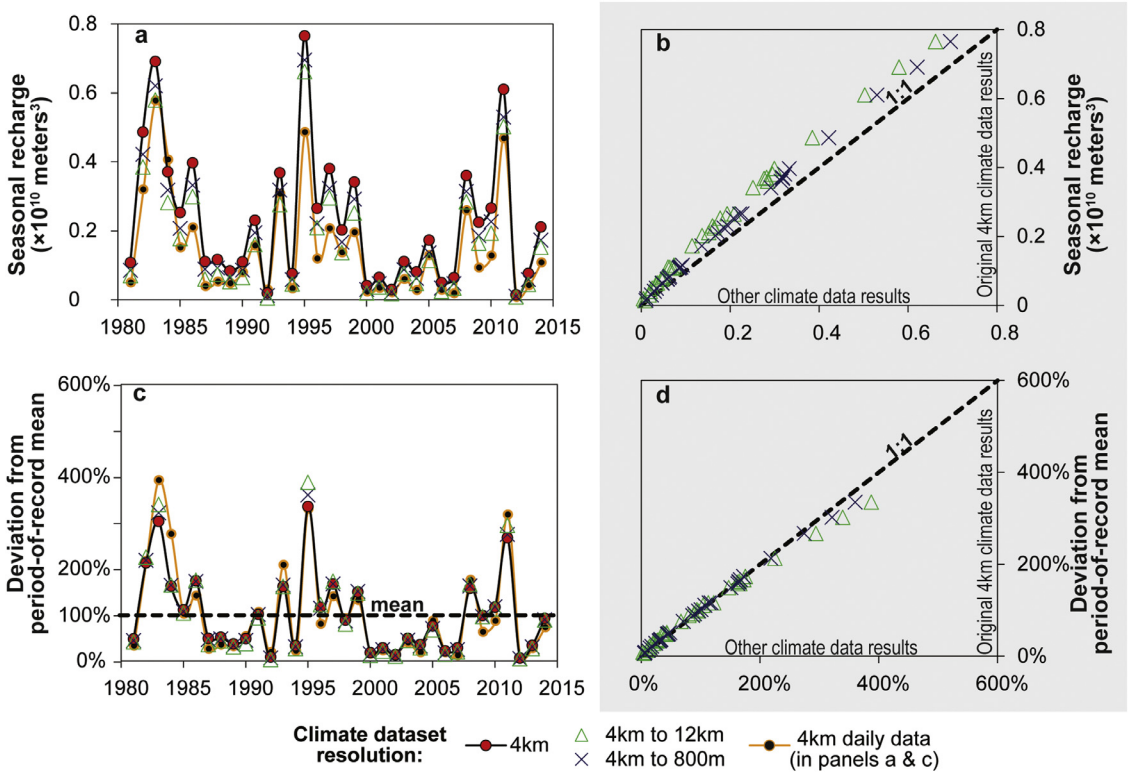

Fig. 9. Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800 m, ~4 km, and ~12 km monthly climate data. Simulation results from daily ~4 km climate data provided for reference. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

daily ~4 km climate data results is 4.8%. For the most part, water-year simulation results for the 1982–2014 time period using monthly climate data are similar among all spatial resolutions and between ~4 km daily and all monthly resolutions, particularly when comparing deviation of recharge from POR means.

3.3.3. Seasonal comparisons

As seen with simulated recharge results using daily climate data over seasonal time spans, the magnitude of recharge results from simulations using monthly climate data were more variable among the different spatial datasets for the summer (JJA; Fig. 9) and fall (SON; Fig. S11 in the supplementary material) months than for winter (DJF; Fig. S12 in the supplementary material) or spring (MAM; Fig. S13 in the supplementary material). The magnitude of simulated recharge in the summer months of JJA, which account for 27% of the annual simulated recharge using monthly climate data, were less than ~4 km results by median values of 19% and 32% for ~800 m and ~12 km results, respectively. The magnitude of recharge results from the fall months of SON differ from ~4 km results by 25% and 30% for ~800 m and ~12 km results, respectively, but make up only 2% of the annual simulated UCRB recharge using monthly climate data (Fig. S11 in the supplementary material). Recharge trends are more similar among the different spatial scales during all seasons, with the highest median difference of 19% between ~12 km and ~4 km results in SON (Fig. S11 in the supplementary material). For the two seasons of MAM (Fig. S13 in the supplementary material) and JJA (Fig. 9) comprising almost 95% of the annual UCRB recharge, median differences between monthly ~4 km results and other spatial data results was 12% or less (Table 2). In a similar manner to the daily climate data results, differences in simulated recharge in JJA using monthly climate data appears to be related to differences in snowmelt during this time period (Fig. 10).

3.3. Comparison of ~800 m daily and ~12 km monthly results

UCRB recharge from simulations using ~800 m daily and ~12 km monthly data were compared in order to explore the effect of the maximum range in both spatial and temporal data on recharge results. The magnitude of annual simulated groundwater recharge averaged over ten-year periods, moving every year, was greater for the ~800 m daily climate data than for the ~12 km monthly climate data by about 10% over the 1982–2014 time period (Fig. 11a, b). Comparison of results from each climate dataset to their respective POR mean, however, indicate almost identical simulated groundwater recharge trends, with a median difference in results between the two climate datasets of less than 2% (Fig. 11c, d).

The magnitude of UCRB simulated recharge over water years from 1982 through 2014 using ~800 m daily climate data also were somewhat greater than results using ~12 km monthly data, by a median difference of 11% (Fig. 12a, b). Simulated recharge trends between the two climate datasets were similar, with deviation from the POR mean sometimes greater for the ~800 m daily climate data but sometimes less (Fig. 12c, d), with an overall median difference between the two datasets of 5.9%.

As with results within the daily and monthly time scale comparisons, smaller differences in seasonal results between simulations using ~800 m daily climate data and ~12 km monthly data are seen in the season with largest percentage of UCRB yearly recharge (Fig. 13). The spring months of March–May account for about 73% of the yearly UCRB recharge for both the ~800 m daily and ~12 km monthly simulations, with median differences in simulated recharge magnitude of about 9% and median differences in trends of about 6% (Fig. 13). Recharge in summer (JJA) is less, but still accounts for a substantial 14–21% of simulated annual UCRB recharge. JJA simulated recharge differs between the ~800 m daily and ~12 km monthly simulations by a median of 55%

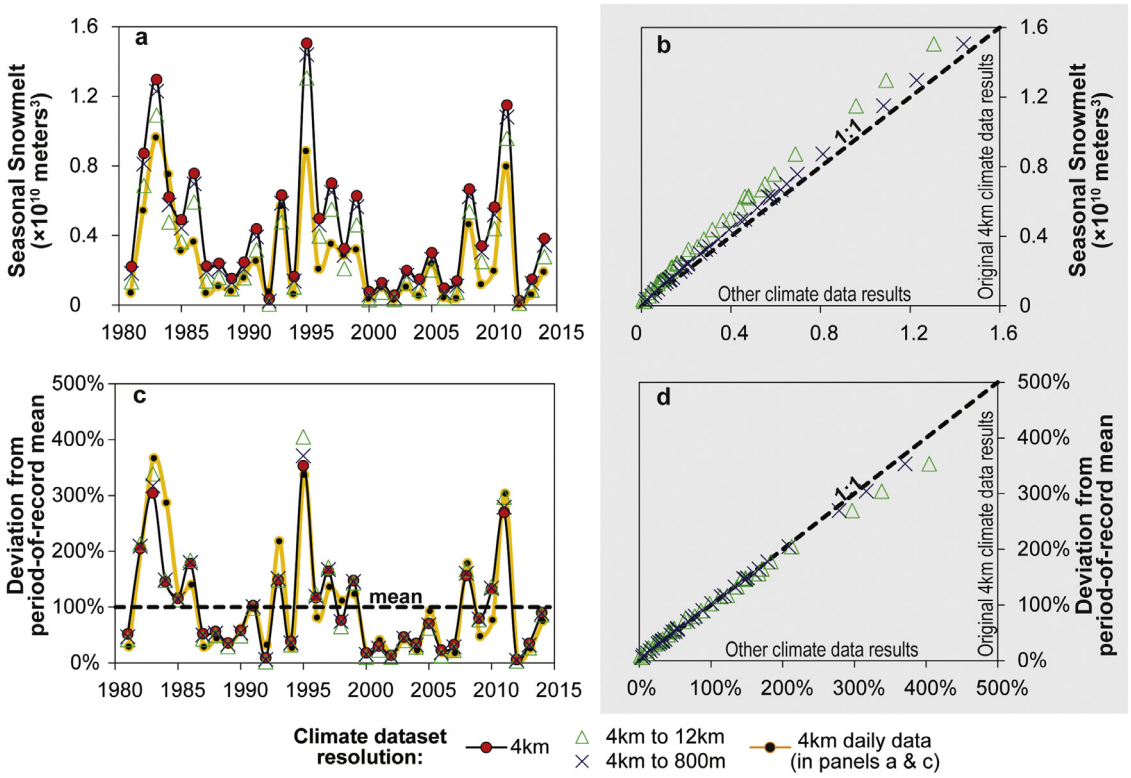

Fig. 10. Simulated snowmelt in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800 m, ~4 km, and ~12 km monthly climate data. Results presented as (a) magnitude of seasonal snowmelt through time, (b) comparison of magnitudes of results from ~4 km climate data with results from ~12 km and ~800 m climate data, (c) change of seasonal snowmelt from period of record mean through time, and (d) comparison of changes from period of record mean from ~4 km climate data results with results from ~12 km and ~800 m climate data.

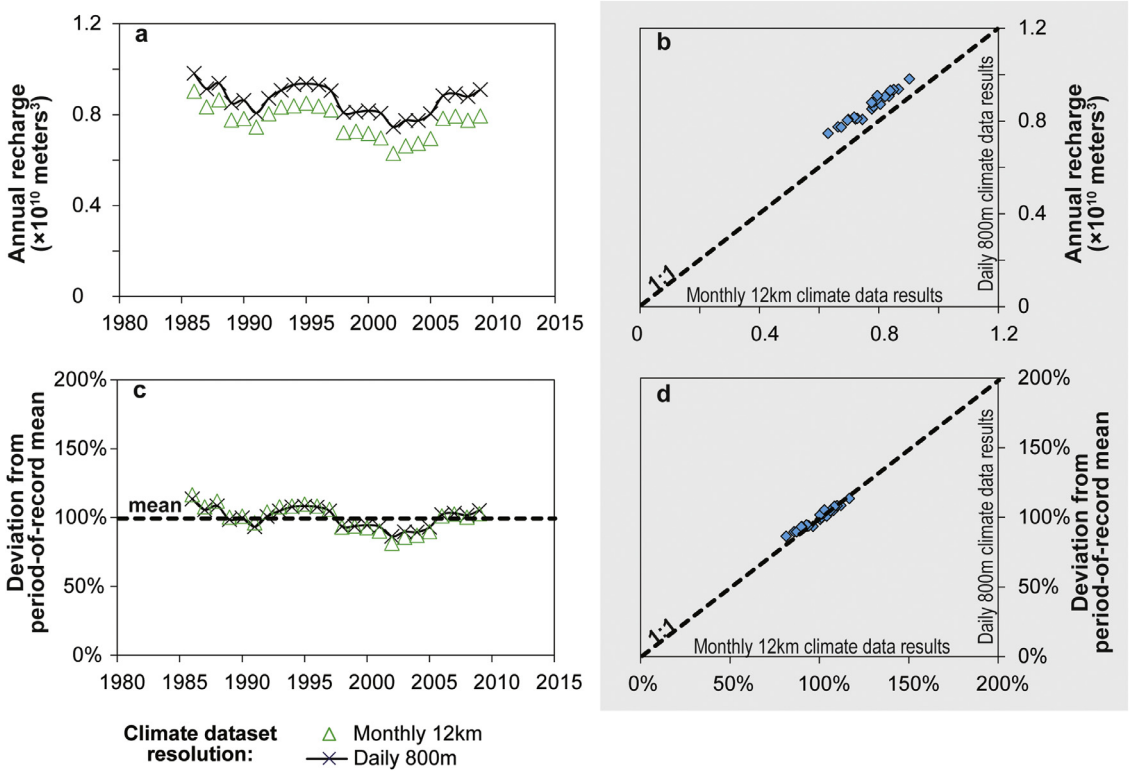

Fig. 11. Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800 m daily and ~12 km monthly climate data. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets. Symbols on time series charts are placed in the middle of the ten-year averaging period.

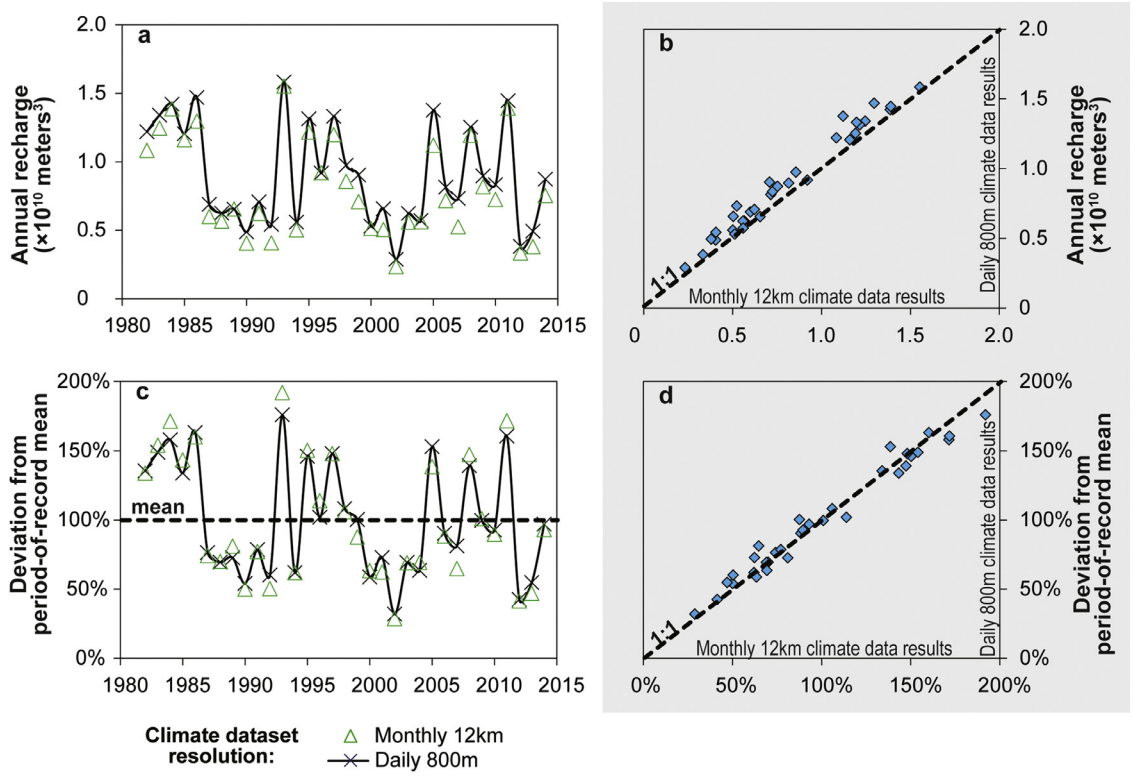

Fig. 12. Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800 m daily and ~12 km monthly climate data. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets.

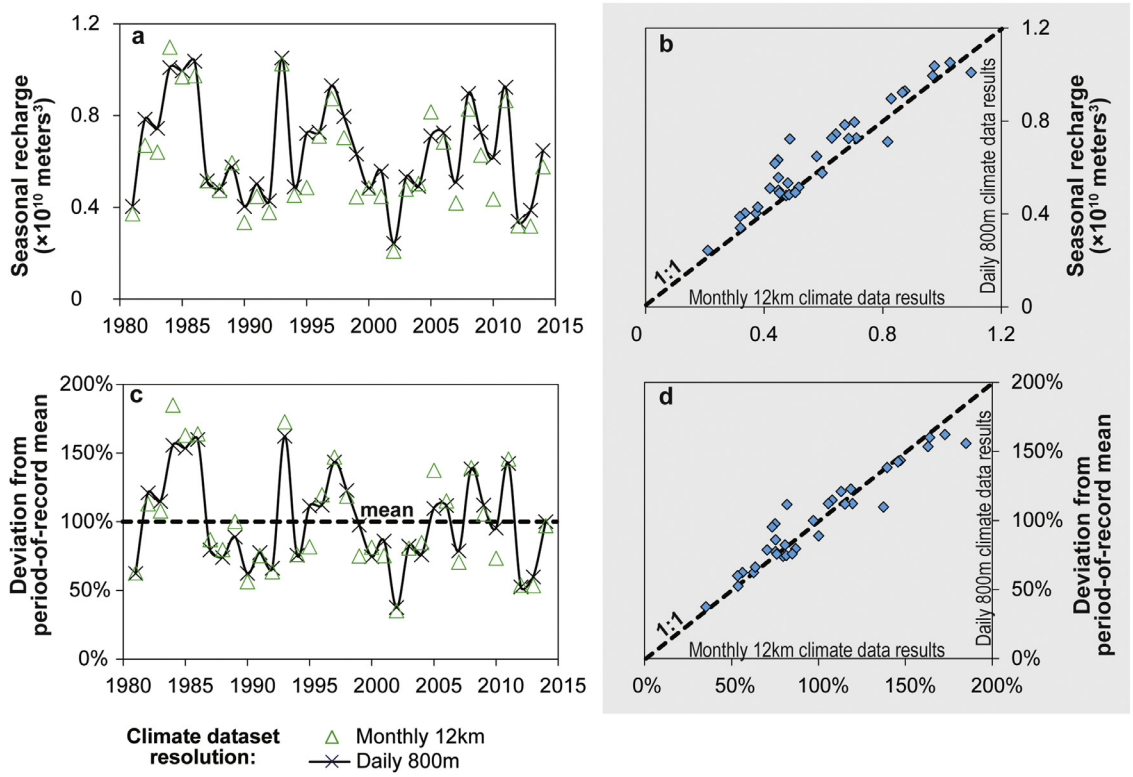

Fig. 13. Simulated groundwater recharge in the upper Colorado River basin in March, April, and May of water years 1982–2014 using ~800 m daily and ~12 km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets.

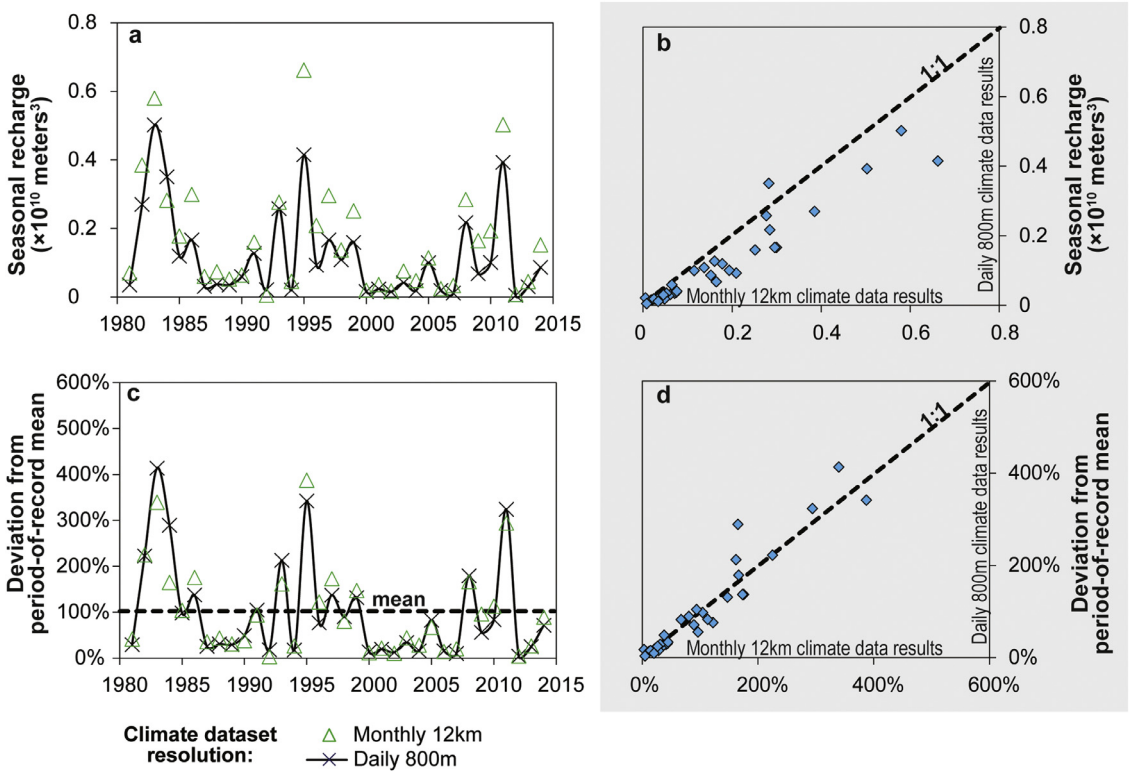

Fig. 14. Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800 m daily and ~12 km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets.

for magnitude comparisons and by 21% for trend comparisons (Fig. 14). Fall and winter seasons together account for about 10% of annual UCRB recharge, and differ between simulations from the two climate datasets by a median 80% or more in magnitude and 34% or more in trend (Figs. S14 and S15 in the supplementary material).

4. Applicability of results to other basins

This investigation of the effect of spatial and temporal scale on simulated groundwater recharge was performed in the upper Colorado River basin, but conclusions from this study may be applicable to other hydrologic regions. With respect to the perceived importance of spatial scale, the UCRB may be a relatively extreme test-case compared with most other hydrologic regions in the U.S. (Fig. 15). A higher percentage of UCRB precipitation falls in a smaller portion of the basin than in all other major hydrologic regions in the U.S., with the exception of the California and Pacific Northwest regions (Fig. 15), and these regions have total precipitation of 2.2 and 5.9 times the precipitation in the UCRB, respectively. Limited high-elevation mountainous headwater areas in the UCRB receive a majority of the basin precipitation, while most of the basin is semi-arid to arid plains that receive little precipitation (Liebermann et al., 1989). Based on this information, it might have been assumed that small spatial discretization of climate data would be important for recharge studies in the UCRB. However, substantial differences in simulated UCRB groundwater recharge were not observed in the spatial scale comparisons, particularly when trends were compared, even between the ~800 m and ~12 km climate datasets. Simulated groundwater recharge in hydrologic regions with more dispersed precipitation might be expected to result in similar or perhaps smaller differences between simulations using different spatial scale data. Conclusions from this study related to the importance of temporal scale, however, may require more investigation before being applied to dissimilar basins elsewhere. In the UCRB, snowpack and subsequent

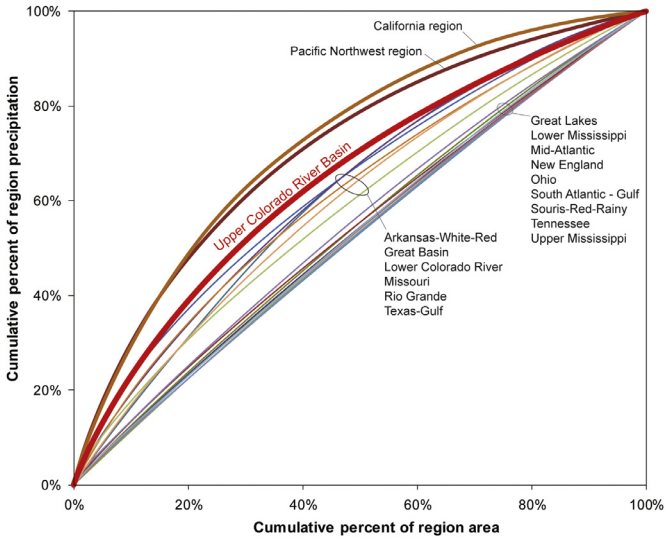

Fig. 15. Precipitation as a function of area for 18 major hydrologic regions in the continental U.S. (PRISM Climate Group, 2016; U.S. Geological Survey, 2018).

snowmelt dominate the hydrology of the basin. The dominance and slower time frame of snowmelt in the basin may have obscured differences in daily/monthly simulation results that may be apparent in other regions. In monsoon-dominated hydrologic systems such as the lower Colorado River basin and the lower Rio Grande, daily precipitation in local areas can be extreme during the summer monsoon. However, winter rain in these regions is generally more effective at producing groundwater recharge than an equivalent amount of precipitation

during summer, owing to lower ET losses from lower winter temperatures (Stonestrom et al., 2007). It is unclear, therefore, if substantial variations in daily monsoon precipitation would result in greater differences between daily and monthly recharge simulations than were seen for UCRB simulations. Other regions with hydrology dominated by snowmelt or regions with precipitation that is distributed over longer time scales might be expected to perform similarly in daily/monthly recharge simulations as this study.

5. Summary and conclusions

While smaller spatial and temporal scale input data allow hydrologic models to simulate more physically realistic processes, it is not clear that increasingly smaller scale data produce substantially different results useful to water resources managers. This study investigated the effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin using the Soil Water Balance model over the water-year 1982–2014 time period. Groundwater recharge was simulated using ~12 km, ~4 km, and ~800 m climate data at both daily and monthly time steps. For both daily and monthly temporal scale simulations, similar recharge magnitude and trend (deviation from period-of-record mean) were seen across all spatial scales for ten-year annual average and water-year comparisons. Seasonal comparisons of results revealed similarities in magnitude and trend of recharge during the spring season of March–May when ~70% of UCRB recharge occurs. Substantial differences were seen in simulated recharge magnitudes in other seasons between different spatial scales, with median differences of as much as 36% from ~4 km results. Comparison of simulated recharge results using the coarsest spatial and temporal climate data, ~12 km monthly scale, with results from the finest scale data, ~800 m daily data, indicated similar small differences in results from the different scales over ten-year moving annual averages, over water years, and during the high recharge months of March–May.

Again, it is important to note the tradeoffs such an analysis presents in terms of the need of using high resolution inputs to a hydrologic model versus the decisions such findings help support. While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, across spatial and temporal scale simulations are substantial during some seasonal comparisons, trends in recharge are almost identical across scales, leading to similar conclusions for water resources managers about change from 'normal'. Especially considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale climate data may be sufficient for simulating changes in groundwater recharge, particularly for providing water resources managers an understanding of trends in recharge over water year or longer time scales.

Conflict of interest

None.

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2018.07.014.

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